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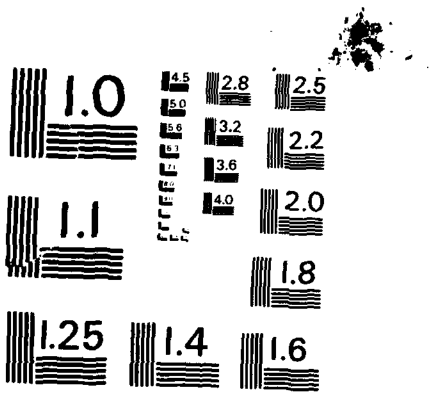

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Turbulent Shear-Layer/Shock-Wave Interactions

Eugene F. Brown

April 1, 1986

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Presentations given at the September 1985 symposium of the International Union of Theoretical and Applied Mechanics (IUTAM) are reviewed. This report concludes that calculation of two-dimensional shock-wave/boundary-layer interaction problems is advancing well. For three-dimensional flows, accurate numerical calculation needs more experimental data to clarify the mechanisms and flow structures involved. Of greatest priority in this area is obtaining accurate unsteady measurements so that the mechanisms of shock oscillation and its results on the flow field can be better understood.

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CONTENTS

TURBULENT SHEAR-LAYER/SHOCK-WAVE INTERACTIONS

1 INTRODUCTION

On 9 through 12 September I attended the International Union of Theoretical and Applied Mechanics (IUTAM) Symposium on Turbulent Shear-Layer/Shock-Wave Interactions at the Ecole Polytechnique in Palaiseau, France. The meeting was organized by an international committee of eight scientists headed by Dr. Jean Délery of the Office National d'Études et Recherches Aérospatiales (ONERA) who served as the Conference Chairman. Approximately 125 people were in attendance, with the US, West Germany, and the UK being particularly well represented. Two scientists from the USSR were also in attendance.

The symposium was divided into three sessions: two-dimensional flows, three-dimensional flows, and unsteady interaction effects. Both experimental results and calculations using Navier-Stokes and zonal-type, boundary-layer/inviscid calculations were presented. I will attempt to summarize the information given in each session and concentrate on what I think were some of the more interesting results. The full proceedings of this symposium will be published soon by Springer-Verlag.

2 TWO-DIMENSIONAL FLOWS

Professor Ha Minh Hieu of Institut de Mechanique des Fluides de Toulouse (IMFT), began the presentations with a review of problems related to the modeling of compressible turbulent flows. He reviewed the different types of modeling, all of which represent extensions of techniques developed for incompressible flows. His feeling is that compressible flows are considerably different and therefore need special modeling, perhaps using statistical methods.

D.A. Johnson of NASA, Ames, presented his Navier-Stokes calculations using an improved nonequilibrium turbulence closure model. The nonequilibrium feature was specifically included to overcome the tendency of eddy-velocity models to predict too rapid a change in the Reynolds shear stress. This occurs in situations in which the main flow field is rapidly distorted, as in separated flows. The model is a hybrid Reynolds-stress/eddy-velocity model patterned after the work of Cebeci and Smith. It reduces to the Cebeci-Smith model for flat plate flows. To account for the effects of large and rapidly changing stream-wise pressure gradients, a simplified Reynolds shear stress equation (an ordinary differential equation for the maximum Reynolds shear stress) is used to determine the eddy-viscosity changes in the stream-wise direction. Impressive agreement with experiments was shown with: (1) Roger Simpson's low-speed, highly separated diffuser experiments, (2) an axisymmetric bump in transonic flow, (3) a super critical airfoil, and (4) a NACA 64A010 airfoil in transonic flow. His model gave much better agreement with experiment than the Cebeci-Smith or the Jones-Launder models (see Figure 1). There was some difficulty in the prediction of the shear stress for the axisymmetric bump downstream of the shock which Johnson ascribed to improper assignment of the length scale. In the case of the supercritical airfoil, the pressure plateau downstream of the shock was picked up and the velocity profiles along the airfoil and in the wake were very well protected. The conclusions were that this particular turbulence model did very well in predicting transonic and low-speed separated flows, even when massive separation was present. A significant advantage is that this turbulence model adds little to the computational time of equilibrium methods and presents no computational stability problems. In the question and answer session which followed, Johnson indicated that the method should be extendable to three-dimensional flows as well.

In her presentation, Mme. B. Escande of Délery's Group demonstrated some of the difficulties of the Jones-Launder (k-ε) calculations. Away from the wall the Euler equations were used. The calculations used a zonal grid

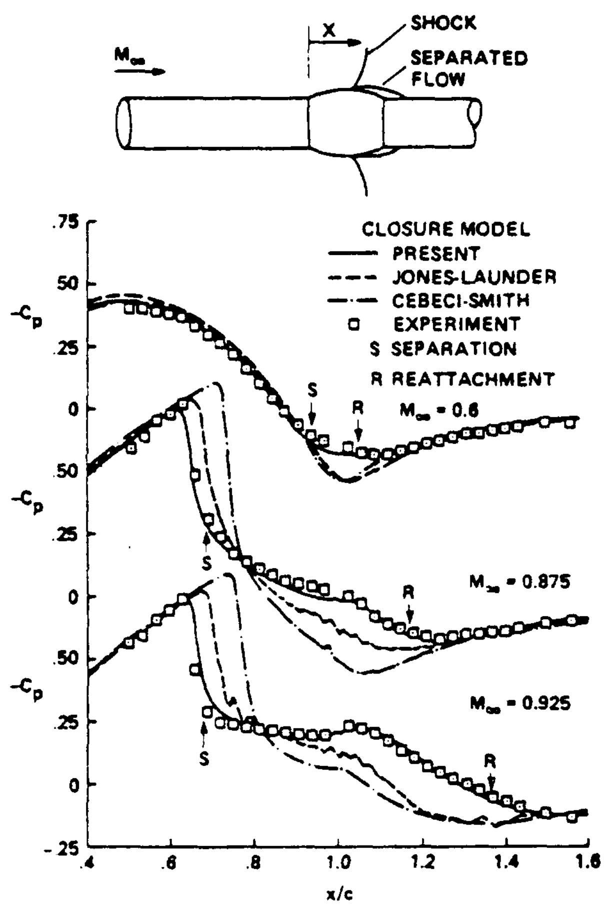

Figure 1. Surface pressure comparisons for the axisymmetric-bump flow.

refinement (dichotomy) method in which the mass spacing was successively halved as the wall was approached. This produced a grid magnification of over 300 as the wall was approached. Calculations were shown using both a mixing-length model and the k-ε model (with a mixing-length model used near the wall). The calculations were compared with the well-known transonic bump experiments done by Délery. The Reynolds number (probably based on the bump cord length) was 2×10^6. Cases at both Mach numbers 1.3 and 1.45 were shown. Although the results of the calculations were better for the k-ε model than the mixing-length model, particularly as regards the pressure variation on the bump, neither predicated the shape factor very well. The maximum shear stress increased far too rapidly with the mixing-length model. (Slightly better agreement with experiment was obtained with the k-ε model.) In addition, the predicated zone of separated flow downstream of the shock was much too large. Similar to the maximum shear stress, the turbulence shear stress increased and decreased much too rapidly in the vicinity of the shock. (Johnson's hybrid scheme was able to overcome this difficulty and predicated a smooth and gradual increase in the turbulent shear stress through the shock.) Escande concluded her presentation by saying that the group planned in the future to investigate algebraic stress models for such calculations. In the question and answer session following her presentation she pointed out that this approach (using the Navier-Stokes equations) represented a departure from the earlier inverse methods of Le Balleur which up until now had been used by this group for calculating such flows.

D. Vandromme of the Institut de Méchanique des Fluides de Lille (IMFL) compared the Baldwin-Lommax turbulence model in a Beam-Warming code with the Cebeci-Smith and k-ε models in a MacCormack implicit code. His conclusion was that in all comparisons the Cebeci-Smith model gave inferior results.

T.C. Tai, David Taylor Naval Ship Research and Development Center (DTNSRDC), and D.E. Edwards, United Technologies Research Center (UTRC), presented their papers on zonal calculations, which involved a combination of inviscid flow methods in the free stream and viscous flow methods near the wall. Edwards concluded that for situations where the lambda shock is present it is absolutely essential to model the vortex sheet behind the shock.

X. Liu (University of Cambridge, UK) then presented his experimental work, including some very fine-resolution laser holograms. His experiments seem quite similar to those done recently by Délery. He investigated several different surface curvatures and made some comparison with calculations. He mentioned that in cases where the experiments showed separation the calculations didn't predict it.

Some very interesting experimental work on a passive control mechanism for altering the character of the shock-wave/boundary-layer interaction was presented by P. Theide, Messerschmitt-Bölkow-Blohm (MBB). It involved stabilizing the position of the shock on a super critical airfoil by using a vented cavity located at the foot of the shock (Figure 2). This work was done in collaboration with P. Krogmann of the Deutsche Forschungs- und Versuchsantsalt für Luft- und Raumfahrt (DFVLR), Göttingen. The experiments were conducted in DFVLR's 1×1-m^2 transonic tunnel on a MBB VA-2 airfoil at a free-stream Mach number of 0.78 and a Reynolds number of 2.5×10^6 with a ventilated cavity covering 15 percent of the cord. Thiede found that the ventilated cavity reduced drag, increased lift, and extended the drag rise and buffet boundaries. These effects resulted from the stabilization of the shock (due to the pressure relief provided the cavity) and a delay of trailing edge separation (due to the reduction in size of the separation bubble behind the shock). The pressure rise through the shock was much more gradual and significantly reduced in amplitude compared with the nonventilated case. The improvement was noticeable particularly at the higher flight Mach numbers where significantly increased lift and reduced drag (up to 45 percent) were shown. At high incidence, separation still occurs; however, the presence of the cavity lessens the severity of buffeting and in some cases suppresses it completely. Thiede indicated that more experiments were needed in order to understand the details of the ventilation mechanism.

In a private discussion which I had with Krogmann after the presentation, I learned that his group and Nagamatsu, Rensselaer Polytechnic Institute, discovered this effect in 1981. In their first tests at the DFVLR, they used active suction and blowing but later discovered that passive ventilation did as well. Initially they used single-slot

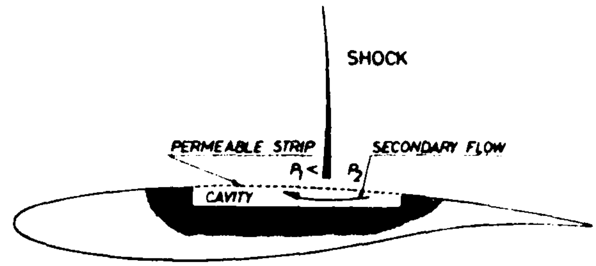

Figure 2. Schematic of an airfoil with a vented cavity at the foot of the shock.

and eventually dual-slot configurations; however, this was insufficient to control the shock at all free-stream Mach numbers so they went to a porous wall instead. Krogmann told me that the principal advantage he sees in using a porous wall is enhanced performance at off-design conditions. He admitted though that the level of improvement which will be seen in full-scale aircraft may not be as great as that reported in the paper, since at the higher Reynolds numbers associated with actual flight conditions, the boundary layer is expected to be thinner. Further experiments are needed to understand better the diameter of the flow in the cavity and the role played by the change in turbulence structure produced by the ventilation.

D. Vandromme compared the performance of turbulence models using the Reynolds transport equations with the Cebeci-Smith, Baldwin-Lomax, and k-ϵ models. The numerical algorithms in which these turbulence models were tested were the Beam Warming and MacCormack (explicit-implicit) codes. The test case chosen was a 16-degree compression corner tested by S.M. Bogdonoff's group at Princeton. All models gave essentially equal results as far as pressure distribution was concerned. However, the Reynolds stress equation model produced slightly better skin friction results. His calculations showed that the shock has relatively little effect on the turbulence quantities. In some cases his calculations showed a slight unsteadiness, and he was unable to get a fully converged solution. He speculated that these effects were probably also present in the experiments.

J.L. Brown of NASA, Ames, specifically addressed the issue of unsteadiness. His particular interest was in shock unsteadiness connected with a cylinder/cone experiment at a Mach number of 2.85 and a Reynolds number of 18×10^6. His calculations, using a steady Navier-Stokes solver, produced poor predictions of the displacement thickness on the ramp, which he attributed to the possible intermittency of the flow. In looking at the unsteady character of the data which he collected he found that the experimental histograms of velocity were very highly skewed. In fact the joint probability density function was bimodal in character. He found that the unsteadiness of the flow can contribute as much as 60 percent of the turbulence shear-stress.

By far the most elegant of the zonal models was presented by R.E. Melink (Grumman). It employed a three-region, three-layer technique and contained an embedded region solved by the full Navier-Stokes equations. Subdividing the flow in this way allows extremely high spacial resolution. Generally acceptable agreement with experiment was obtained; however, the upstream influence of the corner was unpredicted.

D. Aymer de la Chevalerie (Centre d'Études Aérodynamiques et Thermiques, Poitiers) then presented his calculations, using a generalized curvilinear coordinate system. His test case was a 10-degree compression corner at a Mach number of 3 and a Reynolds number 1×10^6. He used the zonal approach in which the Euler equations for the exterior flow were linked to the boundary layer calculations for the interior flow through the local stream line angle provided by the Euler calculations. In this way the coordinate system used in the calculations is linked to the stream lines of the exterior flow. The use of the curvilinear coordinate system produces wall pressures which are in much better agreement with the experiment than if a conventional Cartesian coordinate system had been used. For a case where the wedge angle was increased to 25 degrees, however, the agreement with the experiment was not nearly so favorable.

The final paper on two-dimensional flows was presented by E. Tjonneland for C.K. Forrester. The geometry was rather complex--a supersonic jet issuing into a supersonic coaxial stream through a nozzel having a blunt base. This was the geometry for a recent AGARD Working Group. They used the MacCormack algorithm. The calculations were based on a body-fitted coordinate system which was adjusted as the solution progressed in accordance with the intensity of the gradient found in the calculations. Error norms were used to aid in the detection of inappropriate grid choices. The results of these procedures produced a grid which was well aligned with the stress field and selected such that minimal numerical diffusion will result. As a natural consequence the grid was very highly refined in the wake region. A two-layer algebraic turbulence model was used. Experience with the code indicated that the effect played by mixing in such problems is far less than the effect of inappropriately choosing the grid.

3 THREE-DIMENSIONAL FLOWS

Discussion of experimental results related to three-dimensional flows were reviewed by A.J. Smits (Princeton University). He began by asserting that most so-called two-dimensional flows are in reality three-dimensional. An oblique shock/boundary-layer interaction is a good example. Where a two-dimensional interaction might be expected, surface flow visualizations show an "Owl Face" pattern, which is far from being two-dimensional. In many cases the three-dimensionality of the flow is very complicated and almost impossible to judge from surface flow visualizations. This is particularly true in the vertical motion which appears behind swept shocks and which may produce a local lifting of the stream lines from the surface. At best, the experimental data on such flows is limited because data is difficult to obtain (optical measurements obviously being subject to integrations along the beam path), and because the flow, particularly for a strong shock, is definitely unsteady. Most data have been limited to surface flow visualizations and measurements of the mean surface pressure, which unfortunately do not tell very much about what is happening away from the wall. Ultimately perhaps, our understanding of the intricacies of three-dimensional flows will be obtained from calculations rather than from experiments. Contributing to the validity of this assertion is the fact that three-dimensional interactions are in some ways easier to calculate than two-dimensional ones.

To be sure, problems still remain involving grid generation, resolution and convergence of the calculations, and the adequacy of the turbulence models being used. Identifying and overcoming these problems is difficult because there is so little experimental data available. In many cases the wall pressures agree, but that is not a very sensitive indicator of accuracy. Neither are Pitot pressures away from the wall, yaw angle, and skin friction measurements. In their calculations of the 20-degree corner flow problem investigated by Bogdonoff, Knight and Horstman got good agreement of these quantities but poor agreement of the eddy viscosity. This demonstrates that the main flow is not strongly affected by the wall turbulence. That's the good news: the bad news is that the failure to properly calculate the eddy viscosity is an indication that we don't really understand the flow very well. Further difficulties are introduced in strong interaction problems, that is, where the wedge angle is large. Here, strong unsteady effects come into play. In such situations the shock movement is very important in amplifying the turbulence. Any prediction of such flows must account for this unsteadiness.

For the future, Smits emphasized the need to work on strong interaction problems in order to better understand the structure of the flow and the mechanisms present. Moreover, instantaneous measurements rather than mean flow measurements of pressure and mass flows are required. Off-body as well as surface measurements need to be made and conditional sampling used to correlate the measurements with the position of the shock.

As for future three-dimension computations, Smits pleaded for a stop to calculations using the Baldwin-Lomax algebraic turbulence model. It should be clear by now, he said, that simple turbulence models do not work for flows as complex as these. Models need to be developed which account for unsteadiness of the flow and include the physics for strongly interacting flows. Perhaps assistance in developing such models can be obtained from rapid distortion theory and from the study of several well-known closed-form analytical solutions of relevant phenomenon, such as the Taylor-Green vortex.

P.R. Ashill of the Royal Aircraft Establishment (RAE), Bedford, then presented a particularly interesting piece of work. In a series of careful experiments in their 8'×8' transonic tunnel involving both swept wings and airfoils at Reynolds numbers up to 30×10^6, he devised a high-resolution correlation for the length of the separation bubble, pressure rise, and the occurence of flow breakdown as a function of the boundary layer momentum thickness, Mach number before the shock, and the Reynolds number based on the momentum thickness. There are two uses to which such correlations can be put. The first is to extend the range of experimental data beyond that attainable in the wind tunnel. This is a well-known application of such correlations. The second use is more involved. Since in the experimental tests different momentum thicknesses were produced by different transition strip locations, the correlations can be used to determine where the transition strip should be placed in order to produce wind tunnel simulations which match free-flight conditions. The proper transition strip location is that which produces the same shock position, pressure distribution upstream of the shock, and separation bubble length as the free-flight case. With the transition positioned in this way the resulting airfoil pressure distribution has been found to very nearly agree with free-flight tests.

In the question and answer session following the presentation Bogdonoff raised a question about the generality of the method. He suggested that the correlation might need to be "retuned" for airfoils with higher camber than those used in Ashill's experiments.

Bogdonoff and his students have been involved in experimental measurements of shock-wave/boundary-layer interactions for many years. He echoed some of Smits's comments relative to the difficulty of interpreting from measurements taken on the surface what is happening in a three-dimensional flow. In particular, he took exception to the widely held belief that in some three-dimensional interaction problems the stream lines appear to be leaving the surface. In fact, many three-dimensional flows are very unsteady; consequently, even very detailed flow field measurements taken in the mean may not be very descriptive of what is actually happening. He pointed out that depending upon the frequency response of the measuring equipment being used, the averaging which takes place in such so-called "mean flow measurements" may be anything but the true mean quantity. In fact, today's instrumention is in many respects inadequate for the detailed study of such complex flows. Perhaps computations such as those of Knight and Horstman may be the only way to reveal the details of the flow.

R. Venay (ONERA) presented a three-dimensional extension of the two-dimensional study done by Délery. In these tests the bump was swept sixty degrees in a downstream direction, and static pressure measurements were made on the upper and lower walls along with mean velocities, Reynolds stress components, and histograms made with a three-color laser Doppler velocimetry system. In addition, flow visualizations on the bump and side-walls were made. It is anticipated that this data will provide a useful benchmark for evaluating and developing computational models such as flows. At present, additional processing is under way to fully reveal the character of the turbulence with the hope that the information may, in addition, guide the development of turbulence models for such problems.

M. Cascis (ETA Systems) described the Euler calculations of A. Rizzi. The geometry was an extremely complex one, being a candidate wing for the advanced technology fighter (ADF). The geometry is a cranked, cropped, cambered, and twisted delta wing. Calculations were carried out using a finite volume code developed by Rizzi and run on NASA Langley's Cyber 205. Cases with both 70,000 and 640,000 cells were run. Even with such a large number of cells, mesh independence was not reached. The finer mesh showed many different details of the flow than the coarse one. The coarse and fine mesh lift and drag coefficients differed by 10 percent. This was an extremely complex geometry and so it was not surprising that the pressure coefficients were not predicted very well. The artificial viscosity which is necessary to achieve numerical stability in such calculations was responsible in some measure for this lack of agreement. Although such flows are strongly influenced by viscous effects, such inviscid calculations as these are not without merit: some qualitative aspects of the flow can surely be revealed even though the appearance of the molecular viscosity as an agent for the production of vortices is, of course, missing from the calculations.

M.S. Holden (Calspan Corporation, Buffalo, New York) pointed out some of the difficulties of making experimental measurements of interacting flows under hypersonic conditions. First of all there are only a few experimental facilities and many of these are only capable of transitional Reynolds numbers. This is a special problem at Mach numbers greater than six, since tripping the boundary layer to produce turbulence is not possible. This is because the character of the tripped boundary layer will continue--even far downstream--to be a strong function of the manner in which it was tripped.

4 UNSTEADY INTERACTION EFFECTS

D.S. Dolling (University of Texas at Austin, Texas) presented a review paper on unsteady aspects of shock-wave/boundary-layer interactions. The fact that such interaction problems are naturally unsteady has been known for more than 30 years. In order to understand the interaction mechanism, experimental measurements must address this unsteadiness. Fluctuations in pressure on the order of 20 percent of the mean value are not unusual. A good example of the importance of recognizing unsteady effects is illustrated by the variation in the wall static pressure through a shock/boundary-layer interaction. Dolling maintains that attributing the pressure rise to a distributed compression is incorrect. The correct interpretation of the situation is that it is produced by a single shock which is moving. Thus, what is often described as "upstream influence" is actually an artifact produced by shock motion. The frequency of shock motion is an order of magnitude less than the frequency of the typical turbulent eddies in the boundary layer. The mechanism responsible for shock oscillation is apparently the bursting frequency in the boundary layer upstream of the shock. Measurements of the flow direction near the wall would be extremely helpful for fully understanding this mechanism of shock oscillation.

The work done by Bushnell and his associates at NASA Langley was presented by Smits. They addressed the problem of the influence of shock motion on turbulence structure. The technique was to use MacCormack's explicit Navier-Stokes algorithm to model three cases of shock-motion turbulence interaction. The first problem was the transient response of an eddy convecting subsonically in a locally supersonic flow. The results show that an eddy shocklet forms as the eddy accelerates. In this process a vortex of opposite circulation occurs and the length scale of the initial concentrated vortex is halved. This reduction in turbulence-length scale might explain the decrease in the free shear-layer entrainment rate, which is often observed in shock-containing flows. The second problem was an oscillating wedge in supersonic flow. There the oscillation produced a large increase in the Reynolds stress production and a significant change in the vorticity pattern. The third problem was a shock propagating through a nonisentropic region. The results of the calculations showed the production of a vortex pair. Clearly then the presence of the shock can affect the turbulence scale and influence the character of the vortical motion.

5 SUMMARY

In summary, I would say that calculation of two-dimensional shock-wave/boundary-layer interaction problems is in fairly good shape. By far the most highly developed are the zonal approaches illustrated by the work of Melnik. Until recently, the performance of Navier-Stokes calculations produced results which were inferior to these methods. The Navier-Stokes calculations which Johnson presented in this meeting, however, provided clear evidence that with a proper turbulence model Navier-Stokes calculations can give equivalent accuracy. As far as three-dimensional flows are concerned, accurate numerical calculation will have to await the collection of additional experimental data to clarify the mechanisms and flow structures involved in such problems. Of greatest priority in this area is obtaining accurate unsteady measurements so that the mechanism of shock oscillation and its results on the flow field can be more clearly understood.

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